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DATE: February 6, 2002

TO: Greg Powell, U.S. EPA Work Assignment Manager

THROUGH: Donald T. Bussey, REAC Task Leader/Hydrogeologist DTB

FROM: Terrence Johnson, REAC Senior Groundwater Modeler for TJ

SUBJECT: Revised Technical Memorandum; Evaluation of Groundwater Flow, Extent of Free-Phase LNAPL, and Recovery Options; Industrial Highway Oil Spill Site, Gary, Indiana Work Assignment Number 0-045

BACKGROUND

A significant quantity of light non-aqueous phase liquid (LNAPL) has been discharging to a drainage ditch at the western end of the Gary/Chicago International Airport (Figure 1) for several years. A number of LNAPL seeps were observed by Response Engineering and Analytical Contract (REAC) personnel within the ditch during recent site visits. Over time, the number and extent of the seeps have been increasing. The present groundwater/LNAPL remediation system is ineffective. The United States Environmental Protection Agency/Environmental Response Team Center (U.S. EPA/ERTC) requested that REAC personnel to perform groundwater flow and product recovery modeling for the site to aid in design of a replacement groundwater/LNAPL containment system.

OBJECTIVES

The modeling objectives for this site assessment were to:

- Evaluate groundwater flow conditions at the site,
- Assess the interaction between groundwater flow and the LNAPL product plume movement,
- Evaluate the extent of the LNAPL on the shallow water table at the site, and
- Evaluate options to enhance product recovery and to hydraulically contain the product plume thereby eliminating its discharge to the ditch.

TECHNICAL APPROACH

Specific tasks performed during this exercise included:

- Evaluation and analysis of site hydrologic data,
- Implementation and calibration of a site groundwater model,
- Estimation of free product volume and plume area, and
- Evaluation of extraction/re-injection alternatives including geometry of well array and recovery volumes.

SITE HYDROLOGY

The subsurface geology consists of a 40-foot thick uniform fine to medium grained clean sand over a stiff clay. REAC personnel have assisted with the design and installation of a piezometer and monitor well network, installed within the sand unit with screens set to intersect the water table, to monitor product thicknesses and groundwater flow across the site. Utilizing data obtained from this network, site groundwater flow conditions and the product plume extent were evaluated.

A site groundwater elevation contour map interpolated from monitor well data collected on December 5, 2000 is presented as Figure 2. Where applicable, water table elevations were corrected to account for the presence of LNAPL, using an LNAPL specific gravity of 0.9. The general direction of groundwater flow is to the south-southeast, towards the ditch. The groundwater gradient is approximately 0.004 feet per foot.

Figure 3 depicts the product thickness contours interpolated from monitor well and piezometer data collected on December 5, 2000. There appears to be two distinct product plumes, both plumes oriented northwest to southeast. The larger of the two plumes is to the north, covers approximately five acres, and is approximately 600 feet long along its major axis. The smaller plume covers approximately three acres and is approximately 300 feet long along its main axis. Note that both plumes are open ended and additional monitor wells would be required to fully define the plume and give more accurate estimates of product extent. The plume orientations are consistent with the groundwater flow pattern. Based on this pattern, continued product migration towards the ditch is expected if unabated.

MODELING APPROACH AND MODEL CONCEPTUALIZATION

Modeling Approach

The December 5, 2000 corrected water level data were used to calibrate a site groundwater flow model. The groundwater flow model was not verified. Drawdown and product recovery data from a step drawdown test, conducted to verify the groundwater flow model and calibrate a product recovery model, were of limited value. Frequent groundwater pump cycling made the drawdown data very erratic and not useful for modeling purposes. Additionally, the step tests were performed for periods of time too short meaningful product recovery trends to be evaluated, and hence a product recovery model could not be calibrated.

Figure 4 illustrates the sequence of modeling activities performed. The modeling approach involves the steady state calibration of groundwater flow followed by the simulation of groundwater pumping for product recovery and control as well as the estimation of LNAPL volume.

Conceptual Groundwater Flow Model

The conceptual model of site groundwater flow assumes the following: (1) the aquifer is unconfined, (2) groundwater flow is two-dimensional and horizontal with a uniform aquifer thickness of 40 feet, (3) steady state hydraulic conditions prevail, (4) pumping wells are fully penetrating, (5) the aquifer is heterogenous and isotropic, (6) regional groundwater flow across the site is primarily to the south-southeast towards the ditch (which acts as a sink for groundwater), and (7) local recharge augments regional groundwater flow.

The aquifer of interest is the shallow unconfined 40-feet thick sand formation. Figure 5 illustrates the 130-acre conceptual model domain. The domain covers large areas beyond the site and beyond where hydrologic data is available. It was necessary to extend the model boundaries well beyond the areas so as to minimize the effects of the propagation of on site stresses to the model boundaries.

Regional recharge is considered an areal source in the model. This is modeled as constant over the model domain.

Hydraulic features considered in the conceptual model include pumping wells, a re-injection gallery, and a drain (the ditch). Figure 5 illustrates the location of the hydraulic features considered. Pumping wells were modeled as fully penetrating point sinks with either the drawdown or flux specified; the re-injection gallery was simulated as a fully penetrating line sink with the re-injection rate specified, and the drain was modeled as a fully penetrating line sink using a head dependent flux type boundary condition.

Model Selection

The Trihydro Integrated Model for Environmental Solutions (TIMES) software (Trihydro, 1996) was selected for this analysis. TIMES is one of a family of groundwater flow models that could be used for this exercise. TIMES was specifically selected because (1) it is easy to use, and (2) in addition to groundwater flow, LNAPL flow and recovery can be simulated.

TIMES is a finite-element model that simulates the two-dimensional saturated/unsaturated flow of groundwater, LNAPL, and air. The model generically simulates heterogenous and anisotropic hydraulic properties. Sources and sinks simulated by TIMES include pumping and re-injection, areal recharge, and boundary inflow and outflow. Boundary conditions can be of known heads, fluxes, or mixed.

Finite Element Mesh

Figure 6 illustrates the finite-element mesh used in the modeling exercise. The triangular mesh consists of 6,383 nodes. Nodal spacings are closer in the areas where greater model resolution is desired (i.e., on site, at the ditch, at pumping wells, and at the re-injection gallery). Nodal spacing varies from one foot at the pumping wells to 200 feet on the model periphery.

GROUNDWATER FLOW MODELING

Model Initialization

Two isotropic hydraulic conductivity soil zones were simulated (Zone 1, the area of interest, and Zone 2, the peripheral areas). Both zones were initially assigned a conductivity of 20 feet/day. Both soil zones are depicted on Figure 7.

Initial hydraulic heads were interpolated from the data measured on December 12, 2000 and extrapolated to the model boundaries. Table 1 presents the measured hydraulic heads used to initialize the model. In addition to the measured data, *dummy* groundwater elevation data were placed outside the model boundary to constrain the interpolation where hydrologic data were unavailable. The Kriging algorithm in the TIMES model was used to interpolate the data. Figure 8 is a contour of the model's initial potentiometric surface.

A 40-foot saturated thickness was simulated. Regional recharge was initially added at the rate of six inches/year.

Model Calibration

The model was calibrated to determine the parameters and stresses that will simulate the measured water levels and fluxes to within some prescribed level of accuracy. For this model, a root mean square error (RMSE) and a mean absolute deviation (MAD) of less than 10 percent of the maximum measured head difference across the site is considered adequate. The maximum measured head difference across the model domain is approximately 2 feet (Table 1); therefore, the calibration criteria for this exercise are a RMSE and a MAD of less than 0.2 feet.

The model was calibrated by trial and error to the measured heads assuming they were at steady state. Simulated and measured groundwater levels were compared and model parameters adjusted until the calibration criteria were met. The model parameters adjusted during model calibration were hydraulic conductivity and recharge.

The final regional recharge was two inches/year. The final conductivity values were 15 and 20 feet/day for zones one and two, respectively.

Table 1 presents the observed and simulated hydraulic heads and the residual error (observed minus simulated head). The RMSE and the MAD at the end of calibration were 0.16 feet and 0.14 feet, respectively. Both parameters are within 8 percent of the maximum head difference across the model, which is acceptable. The mean error (the arithmetic average of the residuals) (ME), an indicator of model bias, was also calculated. The ME was -0.014 feet. Therefore, the model on average predicts groundwater elevations that are slightly lower than those actually measured.

Figure 9 illustrates simulated groundwater elevation contours with the measured data posted. Observed hydrologic features are preserved by the model. From the site, groundwater flows primarily towards the south southeast and into the ditch.. The ditch acts as a groundwater sink resulting in a groundwater divide along it's length.

SIMULATION OF SCENARIOS

The results of two scenarios simulated to capture free product and control the LNAPL plume migration are presented. Scenario 1 simulated groundwater recovery in six pumping wells with no re-injection (Figure 10). Scenario 2 considered pumping the six recovery wells with re-injection in an infiltration gallery (Figure 11). The recovery wells were divided into two groups of three with wells spaced approximately at 50 foot intervals within both groups. The wells were located within the product plumes to minimize the amount of LNAPL residual generated as a result of pumping. The infiltration gallery location was selected by the U.S. EPA Region 5 On-Scene Coordinator. In both scenarios, drawdown at the wellheads of three feet was specified and pumping rates were simulated.

A cumulative pumping rate of 30 gallons per minute (gpm) was predicted for Scenario 1. Figure 10 illustrates the predicted drawdown contours and well capture zones for Scenario 1. Also shown are the 0.02 foot and the 0.5 foot product thickness contours. Based on the groundwater capture zone relative to the product plumes, this scenario will hydraulically contain the plumes and prevent further LNAPL migration to the ditch. Free product which has migrated towards the ditch, onto airport property, may eventually be recovered at the wells.

A cumulative pumping/re-injection rate of 40 gpm was simulated in Scenario 2. Figure 11 illustrates the predicted drawdown contours and well capture zones for Scenario 2. The re-injection of groundwater results in a groundwater mound that covers approximately 2 acres of the LNAPL plume to the north. Due to re-injection, groundwater will mound to a height of approximately two feet at the re-injection gallery. On Figure 11 note that the mounding is represented as negative drawdown contours. This scenario will also hydraulically contain the plumes and prevent LNAPL migration to the ditch. Free product that has migrated towards the ditch, onto airport property, may eventually be recovered at the wells as well. In addition, the model predicts that all the re-injected water will be recovered by the well array, creating a continual closed-loop system.

ESTIMATION OF LNAPL VOLUME

The December 20, 2000 product thickness data was used to estimate the free product volume at the site. Capillary characteristic typical sand were used in the estimation.

A free product volume of 125,000 gallons is estimated for the site. Of this volume, the plume to the north has 70,000 gallons, and the more southerly plume has 55,000 gallons. Note that because the LNAPL contours are open ended to the northwest (Figure 3), the true product volume estimate is possibly significantly larger.

DISCUSSION AND CONCLUSION

steady-state groundwater flow model was constructed for the Industrial Highway Oil Spill site and 'oining areas. Site hydrologic data were used to calibrate a groundwater flow model. The groundwater model was used to conduct simulations to evaluate a pumping well array and re-injection gallery to ulically contain the plumes and to prevent further LNAPL migration to the ditch, and to concentrate L at the pumping wells for recovery. Both scenarios involved six pumping wells, one with, and one without the re-injection of the recovered groundwater. Both scenarios are predicted to accomplish the remedial objectives. In the re-injection scenario, all the re-injected water and mobilized product, if any, is expected to be recovered at the pumping wells. Of the two scenarios, the scenario with groundwater re-injection will be less expensive to implement and maintain since no treatment of the recovered groundwater is planned. However, due to re-injecting water, an approximately two acre mound within the larger of the two LNAPL plumes will result. Since the product thickness within this area of the site is less than the mounding, the product at this location will be trapped below the mound and will not be available for recovery. Therefore, even though re-injection may enhance flow gradients and groundwater flow towards the pumping wells, product recovery is expected to be reduced as a result of the mounding effect.

Because of the limited drawdown at the recovery wells (three feet maximum), limited additional smearing of product is expected. REAC recommends that 25 foot deep recovery wells should be adequate to provide the required drawdown and to house necessary recovery equipment.

The model was also used to provide an estimate of the free product volume at the site. A total free product volume of 125,000 gallons, of which 70,000 gallons is found in the more northerly plume and 55,000 in the other plume, is estimated. Typically, between 20 and 40 percent of the free product volume is recoverable. A recovery percentage closer to 20 percent or 25,000 gallons is expected at this site due to the relatively high viscosity and consequent low mobility of the product. The unrecovered product will remain in the subsurface as an immobile residual incapable as migrating as a separate phase.

Note that product recovery was not explicitly modeled in this exercise. Product response was inferred from the groundwater response and it was assumed that the product capture zone will be the same as the groundwater capture zone. However, in reality, a smaller product capture zone than the groundwater capture zone will be expected due to the lower product mobility compared to water. The product mobility will be lower than groundwater due to the higher viscosity of the product and the smaller product thicknesses compared to the aquifer saturated thickness.

The fact that the groundwater model was not verified reduces the credibility of the model results. Verification is the process whereby data obtained under an independent set of stresses from the calibration data set are used to the test the goodness of the model parameters calibrated. This process serves to improve the credibility of the model results. Product volume estimates are even more uncertain since calibration and verification of a product recovery model has not been simulated.

Groundwater monitoring data collected subsequent to operation of the recovery system, if implemented, could be used to verify the groundwater model, calibrate a product recovery model, and provide more reliable model estimates.

REFERENCES

TriHydro Corporation, 1996, *TriHydro Intergrated Modeling for Environmental Solutions*; TIMES Version 2.1 User's Guide, Laramie, Wyoming.

cc: Steve Faryan, U.S. EPA Region 5 On-Scene Coordinator
Central File

Table 1
Observed and Simulated Hydraulic Heads During Model Calibration
Industrial Highway Oil Spill Site
Gary, Indiana

Monitor Well	Observed head (feet)	Simulated Head (feet)	Residual (feet)
MW-1	93.44	93.34	-0.10
MW-2	92.62	92.89	0.27
MW-3	94.31	94.07	-0.24
MW-4	93.45	93.51	-0.06
MW-5	93.08	93.25	0.17
MW-6	92.64	92.79	0.15
MW-7	93.76	93.80	0.04
MW-8	93.06	93.22	0.16
MW-9	92.39	92.30	-0.09
MW-10	92.85	92.91	0.06
MW-11	93.79	93.56	-0.23
MW-12	94.37	94.29	-0.08

Maximum observed head difference: 0.20 feet
Mean absolute error: 0.14 feet
Root mean square error: 0.16 feet
Mean error: +0.014 feet

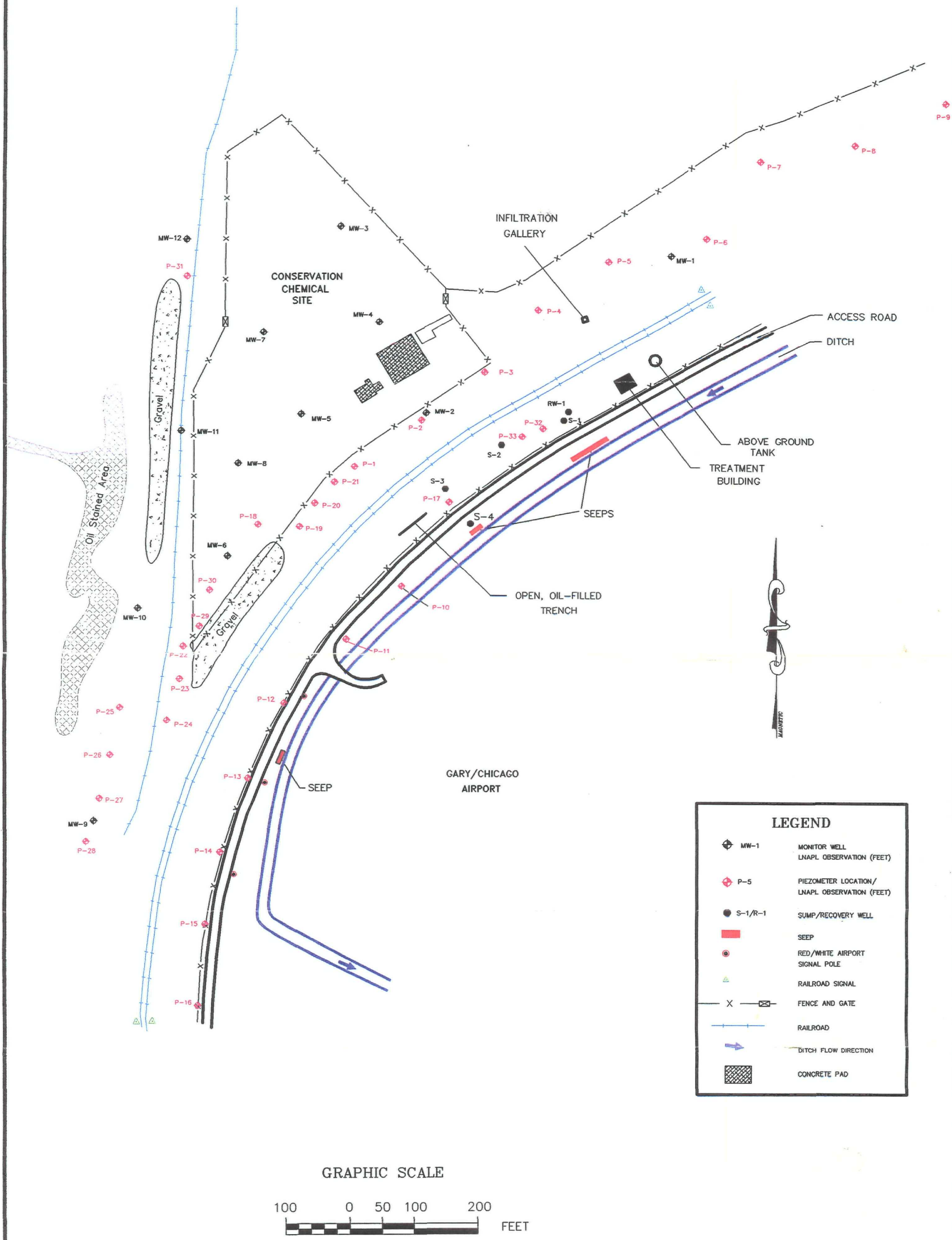

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FIGURE 1
SITE MAP
INDUSTRIAL HIGHWAY OIL SPILL SITE
GARY/CHICAGO AIRPORT
FEBRUARY 2002

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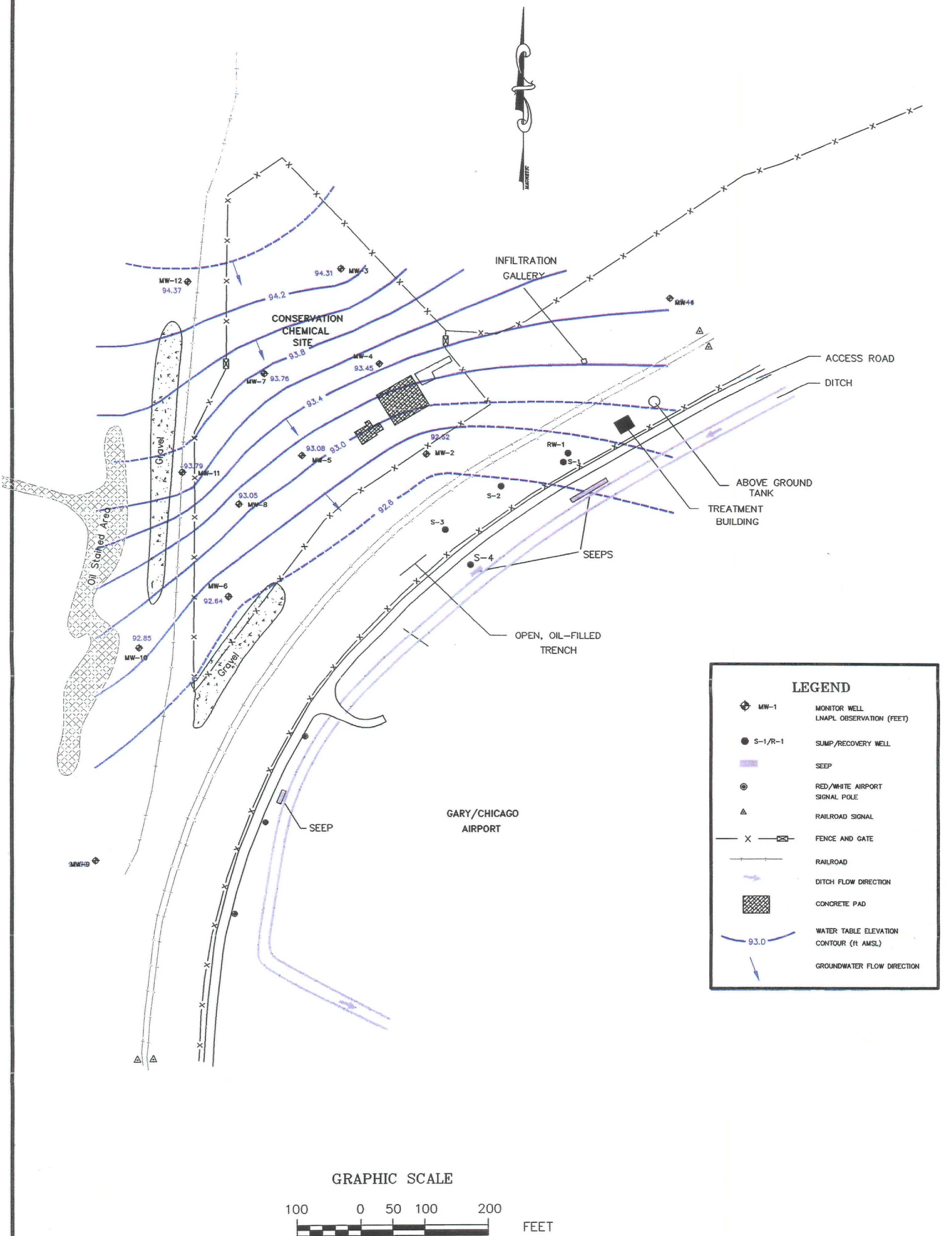

FIGURE 2
CORRECTED WATER TABLE ELEVATION CONTOURS (ft AMSL) AND ACTUAL DATA (POSTED) ON 12/5/2000
INDUSTRIAL HIGHWAY OIL SPILL SITE
GARY/CHICAGO AIRPORT
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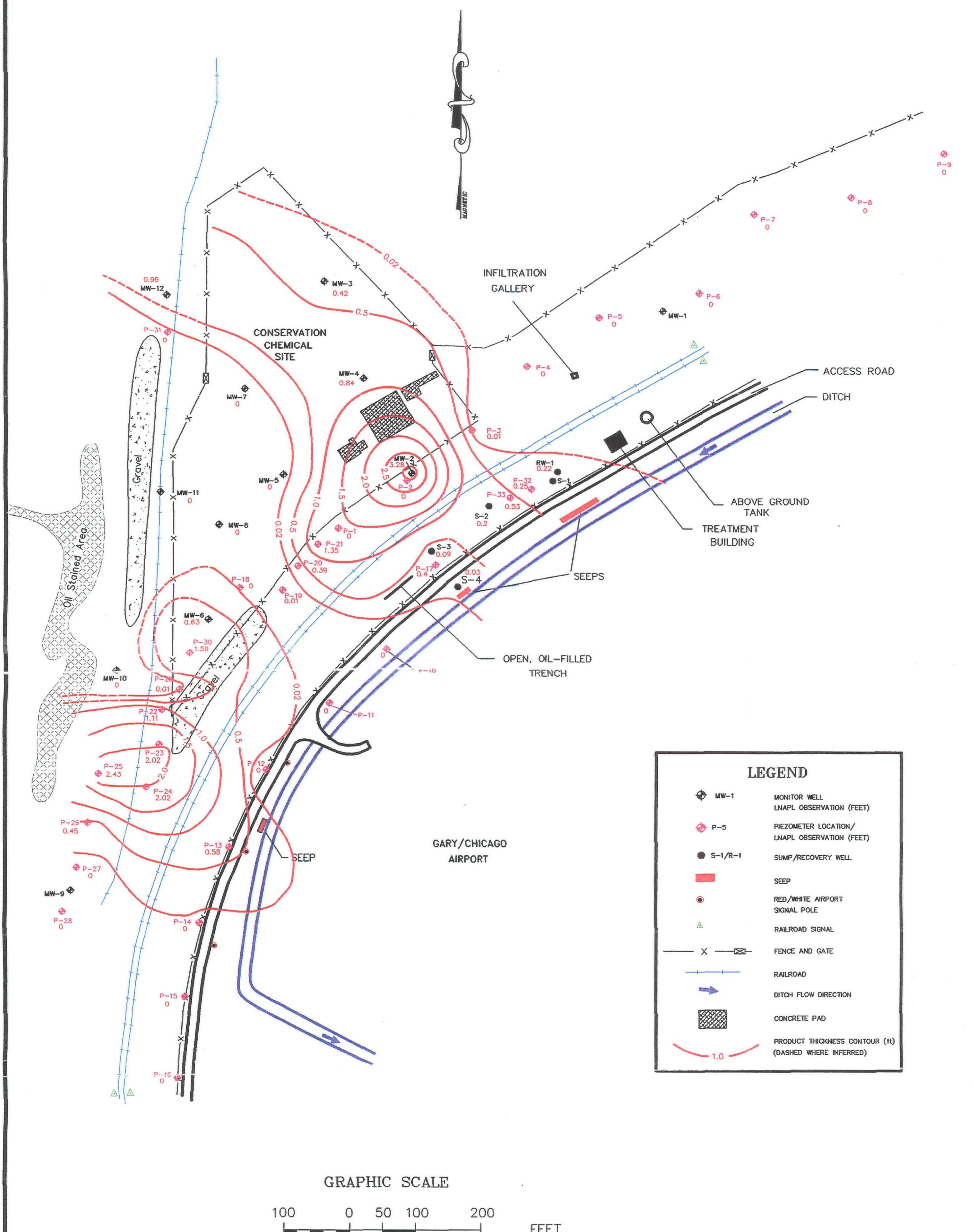

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FIGURE 3
PRODUCT THICKNESS CONTOURS (ft) AND MEASURED DATA (POSTED) ON 12/5/2000
INDUSTRIAL HIGHWAY OIL SPILL SITE
GARY/CHICAGO AIRPORT
FEBRUARY 2002

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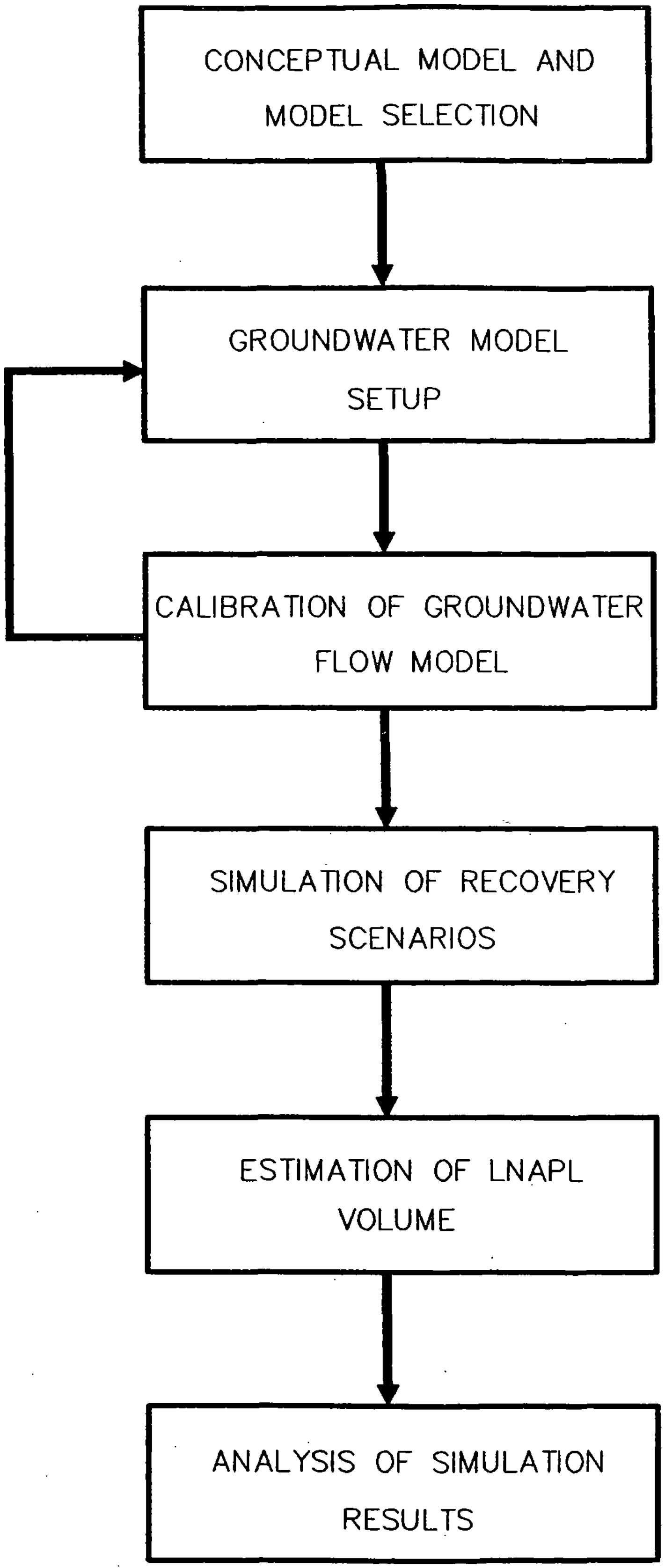

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FIGURE 4
SEQUENCE OF MODELING ACTIVITIES
INDUSTRIAL HIGHWAY OIL SPILL SITE
GARY/CHICAGO AIRPORT
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045/MODELING/FIG_4.DWG

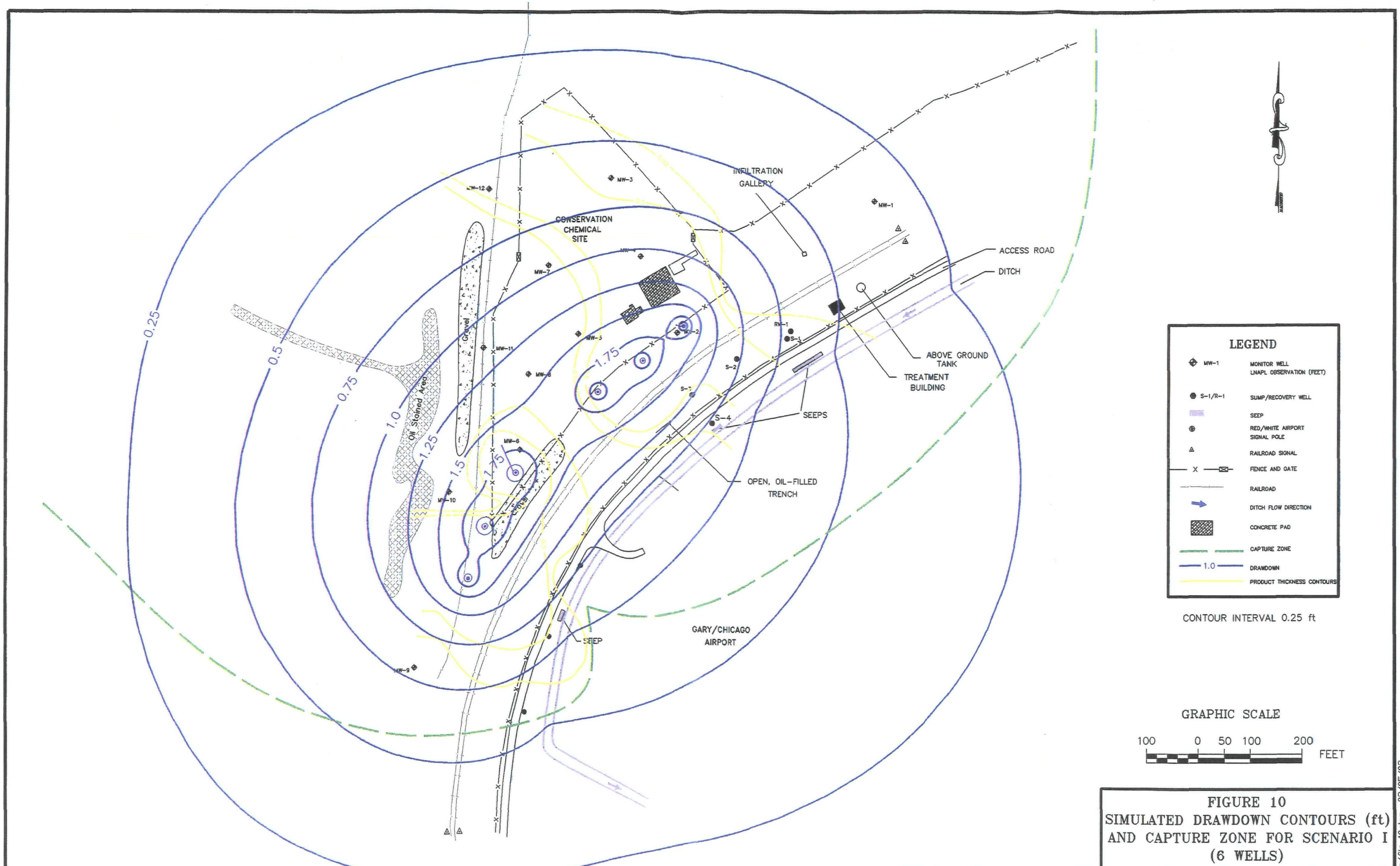

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FIGURE 10
SIMULATED DRAWDOWN CONTOURS (ft) AND CAPTURE ZONE FOR SCENARIO I (6 WELLS)
INDUSTRIAL HIGHWAY OIL SPILL SITE
GARY/CHICAGO AIRPORT
FEBRUARY 2002

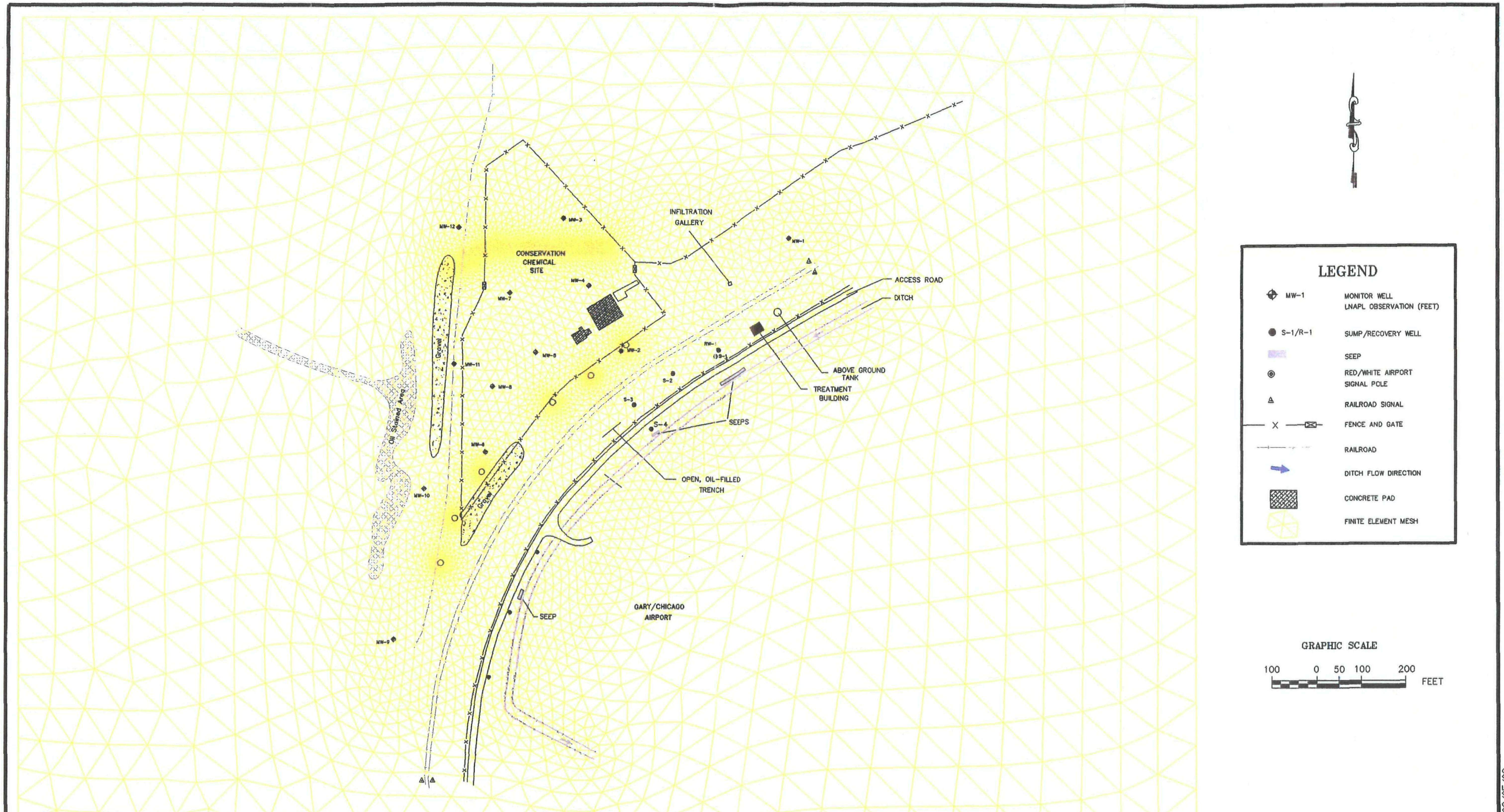

FIGURE 6
FINITE ELEMENT MESH
AND MODEL DOMAIN
INDUSTRIAL HIGHWAY OIL SPILL SITE
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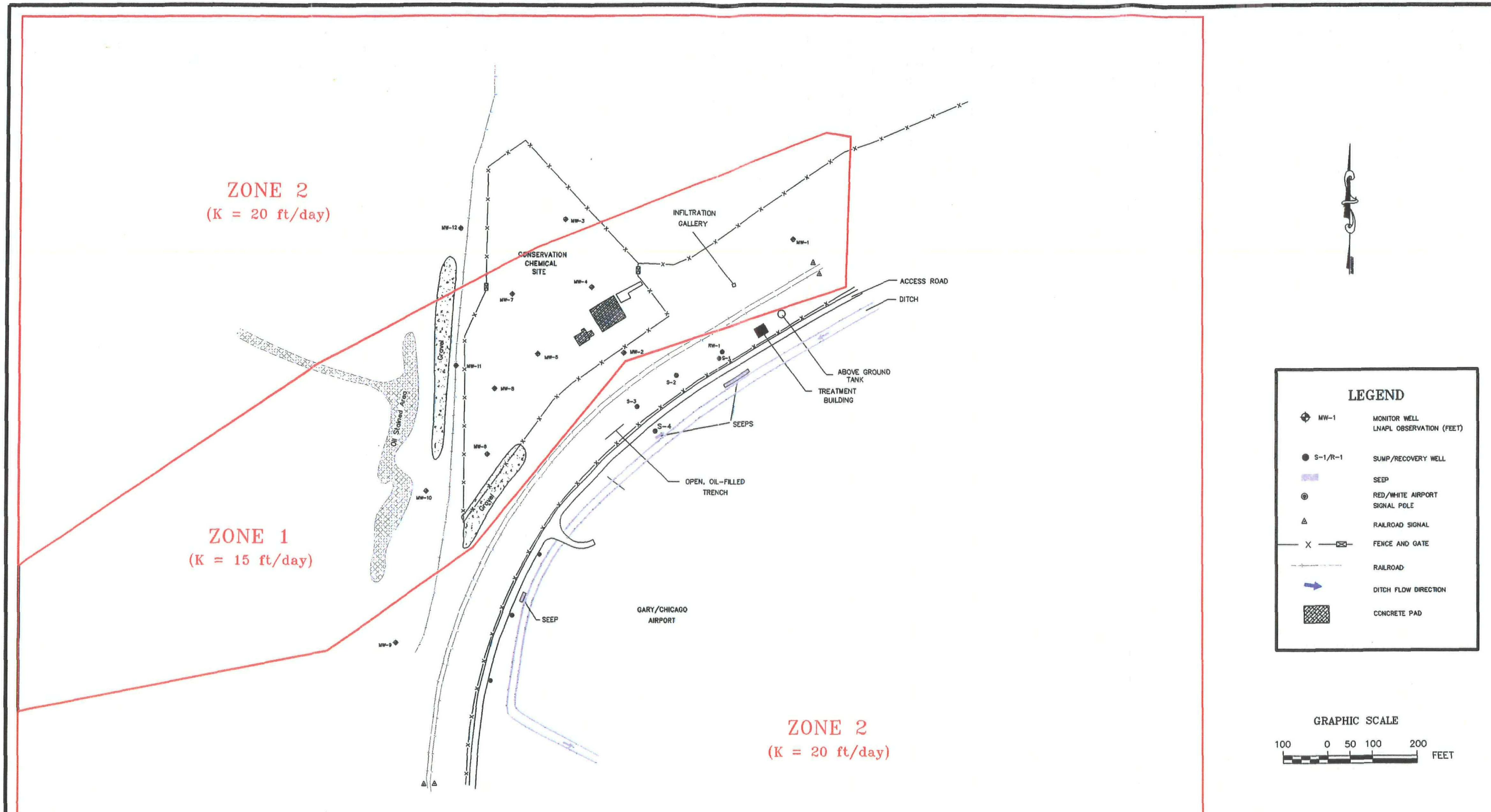

FIGURE 7
HYDRAULIC CONDUCTIVITY ZONES
SIMULATED
INDUSTRIAL HIGHWAY OIL SPILL SITE
GARY/CHICAGO AIRPORT
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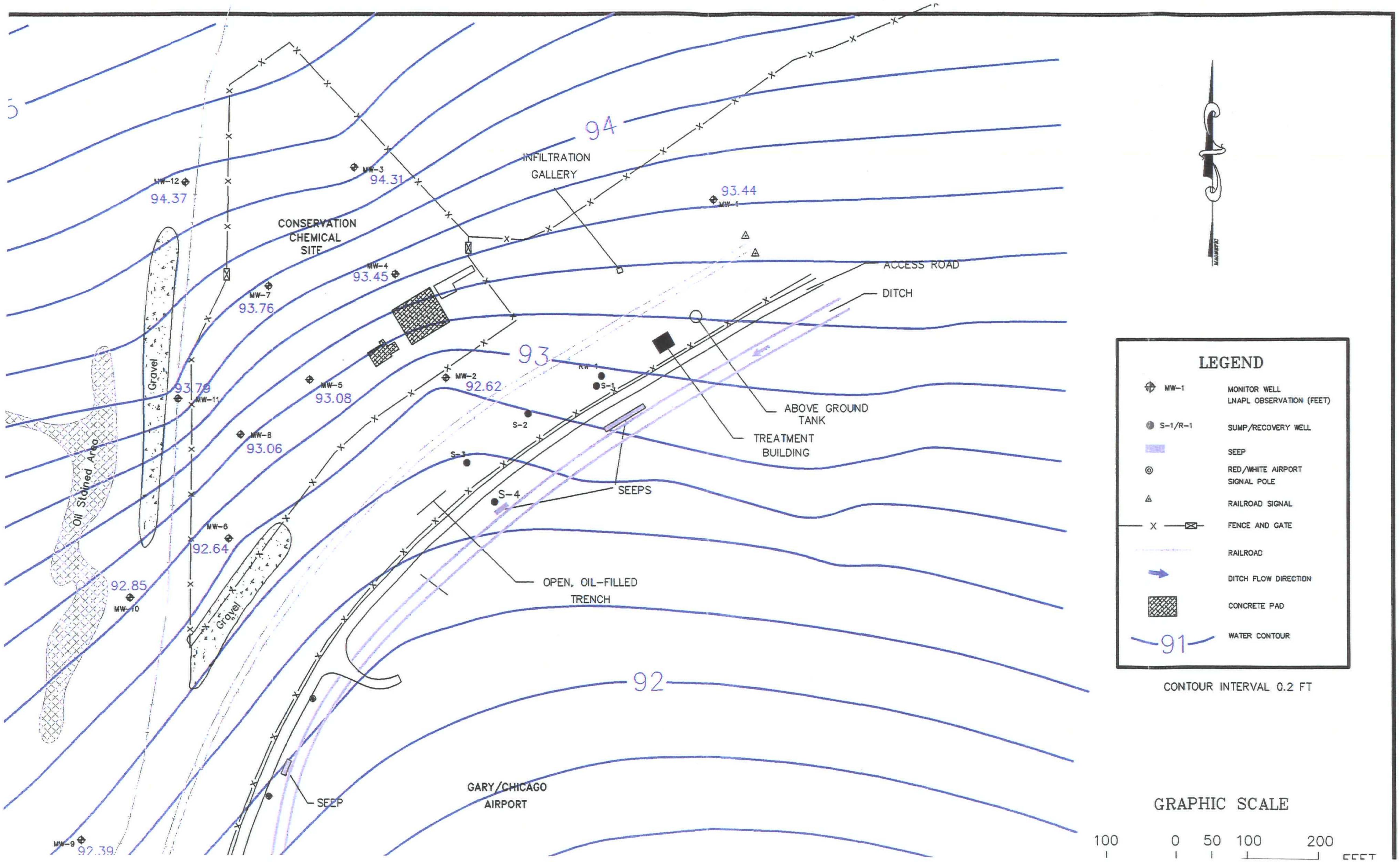

94
93
92
MW-12
94.37
MW-3
94.31
MW-4
93.45
MW-7
93.76
MW-5
93.08
MW-2
92.62
MW-8
93.06
MW-11
93.79
MW-6
92.64
MW-10
92.85
MW-9
92.39
MW-1
93.44
CONSERVATION
CHEMICAL
SITE
INFILTRATION
GALLERY
ACCESS ROAD
DITCH
ABOVE GROUND
TANK
TREATMENT
BUILDING
SEEPS
S-1
S-2
S-3
S-4
OPEN, OIL-FILLED
TRENCH
SEEP
GARY/CHICAGO
AIRPORT
Gravel
Oil Stained Area
LEGEND
MW-1
MONITOR WELL
LNAPL OBSERVATION (FEET)
S-1/R-1
SUMP/RECOVERY WELL
SEEP
RED/WHITE AIRPORT
SIGNAL POLE
RAILROAD SIGNAL
FENCE AND GATE
RAILROAD
DITCH FLOW DIRECTION
CONCRETE PAD
91
WATER CONTOUR
CONTOUR INTERVAL 0.2 FT
GRAPHIC SCALE
100
0
50
100
200

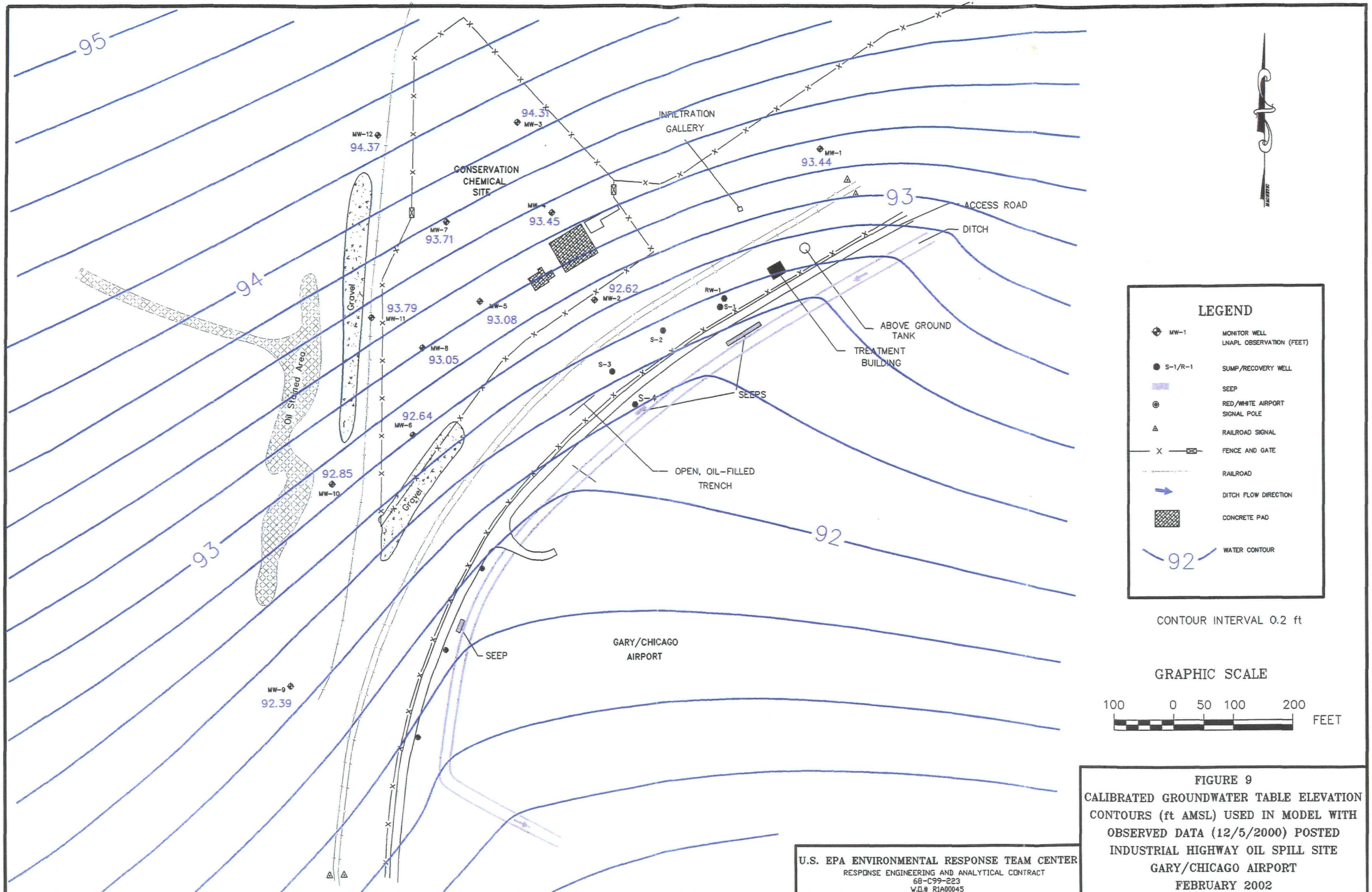

FIGURE 9
CALIBRATED GROUNDWATER TABLE ELEVATION CONTOURS (ft AMSL) USED IN MODEL WITH OBSERVED DATA (12/5/2000) POSTED
INDUSTRIAL HIGHWAY OIL SPILL SITE
GARY/CHICAGO AIRPORT
FEBRUARY 2002

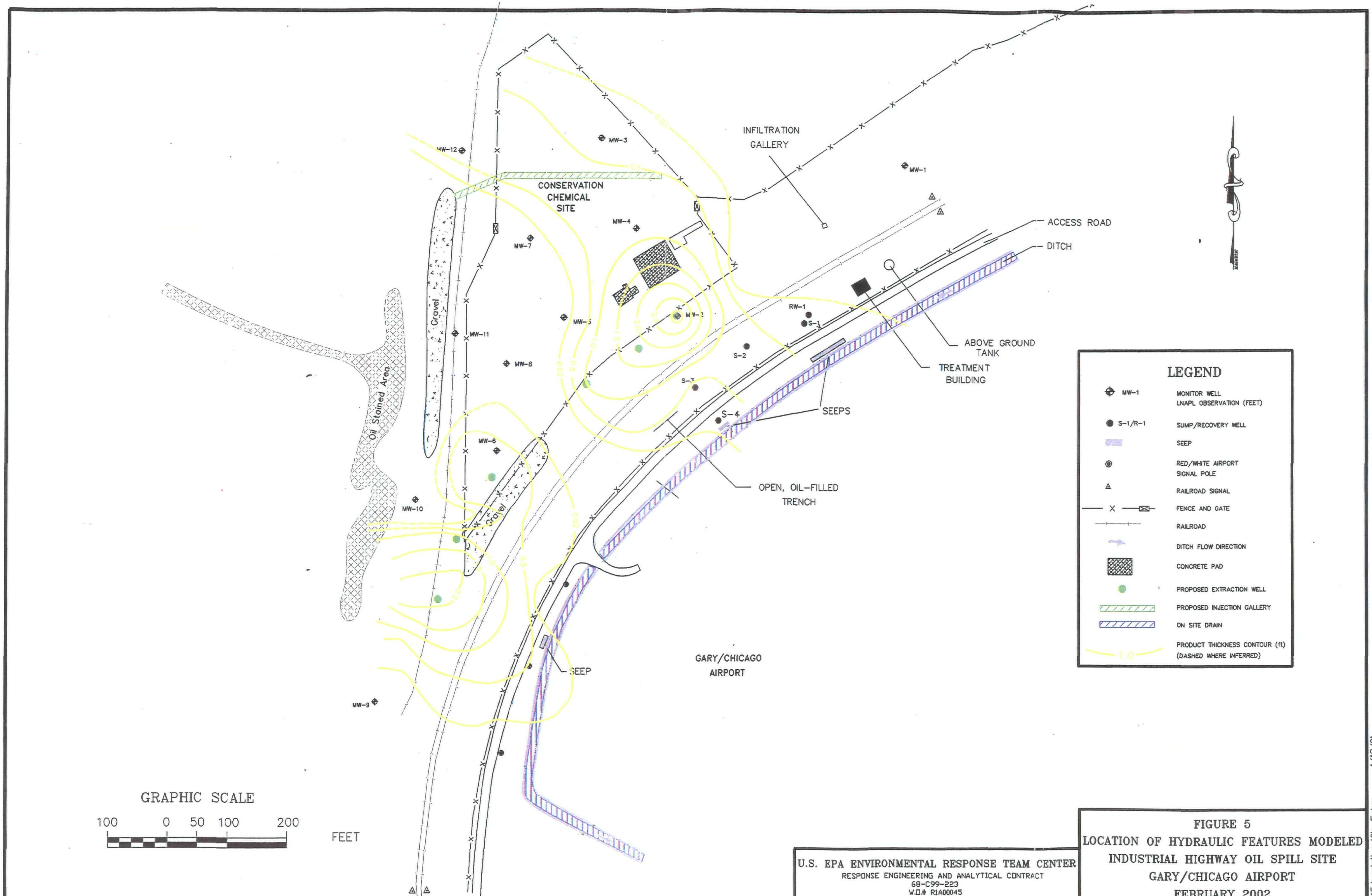

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FIGURE 5
LOCATION OF HYDRAULIC FEATURES MODELED
INDUSTRIAL HIGHWAY OIL SPILL SITE
GARY/CHICAGO AIRPORT
FEBRUARY 2002

045/modeling/fig-5.dwg 4/12/01